Low-Mass Dark-Matter Hint from CDMS II, Higgs Boson at LHC, and Darkon Models

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Abstract

The underground CDMS II experiment searching directly for weakly interacting massive particle (WIMP) dark matter (DM) has observed three WIMP-candidate events corresponding to a WIMP mass of order 9 GeV. Since the confidence level of the finding is only about three sigmas, it does not yet offer conclusive evidence for WIMPs. Nevertheless, interestingly, although the parameter region implied by the signal hypothesis seems to be already excluded mainly by the current strictest limits from the XENON experiments, most of this tension can go away if the WIMP interaction with nuclei violates isospin symmetry. This motivates us to explore some of the implications for models in which a real gauge-singlet scalar particle, dubbed the darkon, serves as the WIMP, taking into account the recent discovery of a Higgs boson at the LHC and Planck determination of the DM relic density. In the simplest scenario, which involves only the standard model plus a darkon, the Higgs boson is largely invisible due to its decay into a pair of darkons having the WIMP mass suggested by CDMS II and hence cannot be identified with the one found at the LHC. We find, on the other hand, that in a two-Higgs-doublet model supplemented with a darkon there is ample parameter space to accommodate well both the new CDMS II and LHC data, whether or not the darkon-nucleon interaction is isospin violating.

I. INTRODUCTION

The latest direct search for weakly interacting massive particle (WIMP) dark matter (DM) carried out by the CDMS Collaboration has come up with a tantalizing possible hint of its collisions with ordinary matter [1]. Their analysis of data collected using the CDMS II silicon detectors has turned up three events in the signal region with confidence level of about 3 sigmas. If interpreted to be due to spin-independent WIMP-nucleon scattering, the new data favor a WIMP mass of 8.6 GeV and scattering cross-section of $1.9 \times 10^{-41}\,\mathrm{cm}^2$.

Because of the relatively low statistical significance of this finding, it still does not provide definitive evidence for the existence of WIMPs [1]. Nevertheless, it has added to the excitement previously aroused by the excess events seen in the DAMA, CoGeNT, and CRESST-II direct detection experiments and conceivably of WIMP origin as well [2–4]. Like the CDMS II observation, the earlier findings are suggestive of a WIMP mass in the region roughly from 7 to 40 GeV and WIMP-nucleon scattering cross-sections of order 10^{-42} to 10^{-40} cm^2, although the respective ranges preferred by the different experiments do not fully agree with each other.

The CDMS II result has also contributed to the ongoing tension between these potential WIMP indications and the null results of direct searches by the XENON Collaboration and others [5–11]. This puzzle on the experimental side is yet to be resolved comprehensively, and presently for WIMP masses under 15 GeV the null results are still controversial [12]. It is intriguing, however, that for the WIMP parameter space implied by CDMS II most of the conflict with the exclusion limits from the latter experiments can disappear if the WIMP interactions with nucleons are allowed to violate isospin symmetry, as will be shown later.

It is then of interest to see how simple models can account for these developments regarding the light-WIMP hypothesis, taking into account the recent discovery of a Higgs boson with mass around 125 GeV at the LHC [13] and determination of the DM relic density by the Planck Collaboration [14]. Here we will focus on a scenario in which a real gauge-singlet scalar particle called the darkon plays the role of WIMP DM.

In the minimal darkon model [15, 16], which is the standard model (SM) slightly expanded with the addition of the darkon (SM+D), the Higgs boson having a mass of 125 GeV will decay predominantly into a darkon pair if the darkon mass $m_D \sim 10\,\mathrm{GeV}$ as suggested by CDMS II. This Higgs boson would then be largely invisible, very unlike the one found at the LHC [13].

In order to accommodate both a Higgs boson consistent with LHC data and a light darkon, the SM+D must therefore be enlarged. One of the simplest extensions contains an extra Higgs doublet [17–19]. In a two-Higgs-double model plus a darkon (THDM+D), the lighter CP-even Higgs boson can be SM-like and the heavier one primarily responsible for the light-darkon annihilation which reproduces the observed DM relic density [18, 19].

In the next section, we explore some of the implications of the latest CDMS II, LHC, and Planck measurements for the THDM+D. We will consider both the cases of WIMP-nucleon interactions with and without isospin symmetry.

II. TWO-HIGGS-DOUBLET MODEL PLUS DARKON

For the Higgs sector of this model, we adopt the so-called type III of the two-Higgs-doublet model (THDM), in which the quarks and charged leptons each couple to both Higgs doublets. Although the type-II THDM+D can also provide a SM-like Higgs boson and a low-mass darkon [18], only the type-III THDM+D one can offer WIMP-nucleon effective couplings with sufficiently sizable isospin violation [19].

Its Yukawa Lagrangian has the form [20]

$$\begin{aligned}\mathcal{L}_{\rm Y} \;=\; & -\bar{Q}_{j,L}\big(\lambda_1^{\mathcal{U}}\big)_{jl}\tilde{H}_1\mathcal{U}_{l,R} - \bar{Q}_{j,L}\big(\lambda_2^{\mathcal{U}}\big)_{jl}\tilde{H}_2\mathcal{U}_{l,R} - \bar{Q}_{j,L}\big(\lambda_1^{\mathcal{D}}\big)_{jl}H_1\mathcal{D}_{l,R} - \bar{Q}_{j,L}\big(\lambda_2^{\mathcal{D}}\big)_{jl}H_2\mathcal{D}_{l,R} \\ & - \bar{L}_{j,L}\big(\lambda_1^{E}\big)_{jl}H_1E_{l,R} - \bar{L}_{j,L}\big(\lambda_2^{E}\big)_{jl}H_2E_{l,R} \;+\; {\rm H.c.}\;, \end{aligned} \tag{1}$$

where summation over $j,l=1,2,3$ is implicit, $Q_{j,L}$ $\big(L_{l,L}\big)$ represent the left-handed quark (lepton) doublets, $\mathcal{U}_{l,R}$ and $\mathcal{D}_{l,R}$ $\big(E_{l,R}\big)$ are the right-handed quark (charged lepton) fields, H_1 and H_2 denote the Higgs doublets, $\tilde{H}_{1,2}=i\tau_2H_{1,2}^*$, and so $\lambda_{1,2}^{\mathcal{U},\mathcal{D},E}$ are 3×3 matrices containing the Yukawa couplings. In the Higgs sector, the CP-even components of the two doublets mix with mixing angle α, while the CP-odd components mix, as do the charged ones, with mixing angle β. The latter is related to the vacuum expectation values (VEVs) $v_{1,2}$ of $H_{1,2}$, respectively, by $\cos\beta=v_1/v$ and $\sin\beta=v_2/v$, with $v_1^2+v_2^2=v^2$ and $v\simeq 246\,{\rm GeV}$. We have followed the notation of Ref. [19] which has a more detailed description of the model.

After the diagonalization of the fermion mass matrices, the flavor-diagonal couplings of the physical CP-even Higgs fields $\mathcal{H}=h,H$ to the fermion mass eigenstate f can be described by

$$\mathcal{L}_{ff\mathcal{H}} \;=\; -k_f^{\mathcal{H}}\,m_f\,\bar{f}f\,\frac{\mathcal{H}}{v}\;, \tag{2}$$

where m_f is the mass of f and for, say, the first family

$$\begin{aligned} k_u^h \;&=\; \frac{\cos\alpha}{\sin\beta} - \frac{\lambda_1^u\,v\,\cos(\alpha-\beta)}{\sqrt{2}\,m_u\,\sin\beta}\;, \qquad & k_u^H \;&=\; \frac{\sin\alpha}{\sin\beta} - \frac{\lambda_1^u\,v\,\sin(\alpha-\beta)}{\sqrt{2}\,m_u\,\sin\beta}\;, \\ k_{d,e}^h \;&=\; -\frac{\sin\alpha}{\cos\beta} + \frac{\lambda_2^{d,e}v\,\cos(\alpha-\beta)}{\sqrt{2}\,m_{d,e}\,\cos\beta}\;, \qquad & k_{d,e}^H \;&=\; \frac{\cos\alpha}{\cos\beta} + \frac{\lambda_2^{d,e}v\,\sin(\alpha-\beta)}{\sqrt{2}\,m_{d,e}\,\cos\beta}\;, \end{aligned} \tag{3}$$

with $\lambda_a^{u,d,e}=\big(\lambda_a^{\mathcal{U},\mathcal{D},E}\big)_{11}$. The corresponding $k_f^{\mathcal{H}}$ for the other two families have analogous expressions. Since only $\lambda_1^fv_1+\lambda_2^fv_2=\sqrt{2}\,m_f$ is fixed by the f mass, λ_a^f in $k_f^{\mathcal{H}}$ is a free parameter, and so is $k_f^{\mathcal{H}}$. Setting $\lambda_1^{\mathcal{U}}=\lambda_2^{\mathcal{D}}=\lambda_2^E=0$ would lead to the type-II THDM+D considered in Ref. [18]. Since the type-III THDM is known to have flavor-changing neutral Higgs couplings at tree level, we assume that in the THDM+D they have their naturally small values according to the Cheng-Sher *ansatz* [21], namely $(\lambda_a)_{jl}\sim\big(m_jm_l\big)^{1/2}/v$ for $j\neq l$. If necessary, one could suppress the effects of these flavor-changing couplings further by increasing the mediating Higgs masses.

In the DM sector of the THDM+D, the stability of the darkon, D, as a WIMP candidate is ensured by requiring it to be a gauge singlet and imposing a discrete Z_2 symmetry under which D is odd and all the other fields are even. The renormalizable Lagrangian for D is then [17]

$$\mathcal{L}_D \;=\; \tfrac{1}{2}\partial^\mu D\,\partial_\mu D - \tfrac{1}{4}\lambda_DD^4 - \tfrac{1}{2}m_0^2D^2 \;-\; \big[\lambda_1H_1^\dagger H_1 + \lambda_2H_2^\dagger H_2 + \lambda_3\big(H_1^\dagger H_2 + H_2^\dagger H_1\big)\big]D^2\;. \tag{4}$$

After electroweak symmetry breaking, $\mathcal{L}_D$ includes the darkon mass m_D and the $DD(h,H)$ terms $-\lambda_h v\, D^2 h - \lambda_H v\, D^2 H$ with

$$m_D^2 \;=\; m_0^2 + \big[\lambda_1 \cos^2\!\beta + \lambda_2 \sin^2\!\beta + \lambda_3 \sin(2\beta)\big] v^2 \;, \tag{5}$$

$$\begin{aligned}\lambda_h \;&=\; -\lambda_1 \sin\alpha\, \cos\beta + \lambda_2 \cos\alpha\, \sin\beta + \lambda_3 \cos(\alpha+\beta) \;, \\ \lambda_H \;&=\; \lambda_1 \cos\alpha\, \cos\beta + \lambda_2 \sin\alpha\, \sin\beta + \lambda_3 \sin(\alpha+\beta) \;,\end{aligned} \tag{6}$$

but no DDA coupling if CP is conserved. Since m_0 and $\lambda_{1,2,3}$ are free parameters, so are m_D and $\lambda_{h,H}$.

To evaluate the darkon annihilation rates, the couplings of h and H to the W and Z bosons may also be relevant depending on m_D. They are given by

$$\mathcal{L}_{VV\mathcal{H}} \;=\; \frac{1}{v}\big(2m_W^2\, W^{+\mu} W_\mu^- + m_Z^2\, Z^\mu Z_\mu\big)\big[h\, \sin(\beta-\alpha) + H\, \cos(\beta-\alpha)\big] \tag{7}$$

from the Higgs kinetic sector of the model [20].

We start our numerical work by identifying the lighter Higgs particle h with the Higgs boson observed at the LHC and fixing the couplings discussed above. The latest measurements on h have begun to indicate that the particle has SM-like properties, but there is still some room in its couplings for deviations from SM expectations. Specifically, according to a number of analyses [22], the current data imply that the h couplings to the W and Z bosons cannot differ from their SM values by more than $\mathcal{O}(10\%)$, whereas the couplings to fermions are less well-determined. Furthermore, the branching ratio of nonstandard decays of h into invisible or undetected final-states can be as high as a few tens percent. All this implies that in general the free parameters k_f^h and $\sin(\beta-\alpha)$ may deviate from unity accordingly and for a light darkon λ_h can be nonzero. For definiteness and simplicity, we take $\beta-\alpha = \pi/2$ and $\lambda_h = 0$, following Ref. [19]. These choices make the h couplings identical to their SM counterparts, in particular $k_f^h = 1$. Moreover, the heavier Higgs boson H now couples to fermions and the darkon according to

$$k_u^H \;=\; -\cot\beta \;+\; \frac{\lambda_1^u\, v}{\sqrt{2}\, m_u\, \sin\beta} \;, \qquad k_{d,e}^H \;=\; \tan\beta \;-\; \frac{\lambda_2^{d,e}\, v}{\sqrt{2}\, m_{d,e} \cos\beta} \;, \tag{8}$$

$$\lambda_H \;=\; \tfrac{1}{2}\big(\lambda_1 - \lambda_2\big) \sin(2\beta) - \lambda_3 \cos(2\beta) \;, \tag{9}$$

but no longer has tree-level couplings to W and Z, the k_f^H formulas for the second and third families being analogous. It follows from these choices that for a light darkon, $m_D < m_h/2$, its annihilation occurs mainly via H-mediated diagrams.

The darkon being the DM candidate, its annihilation cross-section must reproduce the observed DM relic density Ω. Its most recent value has been determined by the Planck Collaboration from the Planck measurement and other data to be $\Omega\bar{h}^2 = 0.1187 \pm 0.0017$ [14], where $\bar{h}$ is the Hubble parameter. To extract λ_H for specific m_D and H-mass, m_H, values, after k_f^H are chosen, we require the darkon relic density to satisfy the 90% CL (confidence level) range of its experimental value, $0.1159 \le \Omega\bar{h}^2 \le 0.1215$. We can then employ the obtained λ_H to predict the darkon-nucleon scattering cross-section and compare it with the direct search data. We will treat in turn the cases where the darkon-nucleon interactions respect and violate isospin symmetry.

In the first case, since λ_1^u and $\lambda_2^{d,e}$ in Eq. (8) are free parameters, again following Ref. [19] we pick for definiteness $k_f^H = 1$. We present the λ_H ranges allowed by the relic data for the low-mass region $5\,\mathrm{GeV} \le m_D \le 50\,\mathrm{GeV}$ and some illustrative values of m_H in Fig. 1(a), where the width of each band reflects the 90% CL range of $\Omega\bar{h}^2$ above.

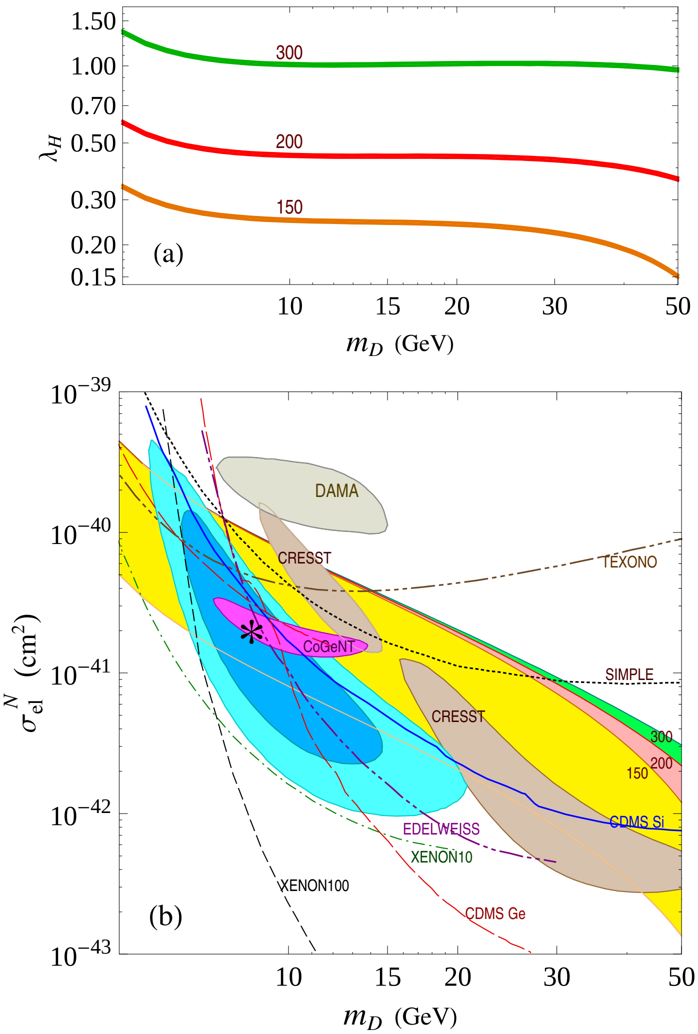

FIG. 1: (a) Darkon-H coupling λ_H as a function of darkon mass m_D for $m_H = 150, 200, 300$ GeV, with the other couplings specified in the text, in the THDM+D with isospin-conserving darkon-nucleon interactions. (b) The resulting darkon-nucleon cross-section $\sigma_{\rm el}^N$, compared to 90% CL upper limits from XENON10 (green dashed-dotted curve) [5], XENON100 (black short-dashed curve) [6], CDMS Ge (red long-dashed curves) [7], CDMS Si (blue solid curve) [11], Stage 2 of SIMPLE (black dotted curve) [8], EDELWEISS (purple dashed-double-dotted curve) [9], and TEXONO (brown dashed-triple-dotted curve) [10]. Also plotted are two 2σ-confidence (light brown) areas representing the CRESST-II result [4], a gray patch compatible with the DAMA modulation signal at the 3σ level [23], the 90% CL (magenta) signal region suggested by CoGeNT reinterpreted including the effect of residual surface event contamination [24], and a blue (cyan) area for a possible signal at 68% (90%) CL from CDMS II [1], with the asterisk marking the maximum likelihood point at $\left(8.6\,\mathrm{GeV}, 1.9\times10^{-41}\,\mathrm{cm}^2\right)$.

The darkon-nucleon scattering occurs via an H-mediated diagram in the t channel. Its cross-section is given by [19]

$$\sigma_{\rm el}^N \;=\; \frac{\lambda_H^2\, g_{NNH}^2\, v^2\, m_N^2}{\pi\left(m_D+m_N\right)^2 m_H^4} \;. \tag{10}$$

The effective H-nucleon coupling g_{NNH} has a rather wide range, $0.0011 \le g_{NNH} \le 0.0032$ [16, 19], because of its dependence on the pion-nucleon sigma term $\sigma_{\pi N}$ which is not well determined [25]. We display in Fig. 1(b) the calculated $\sigma_{\rm el}^N$ corresponding to the parameter selections in Fig. 1(a). The width of each predicted $\sigma_{\rm el}^N$ curve arises mainly from the sizable uncertainty of g_{NNH}. Also on display are the results of recent DM direct searches. One can see that the THDM+D prediction overlaps significantly with the 68%-CL possible signal (blue) region from CDMS II [1], as well as with the signal regions suggested by CoGeNT and CRESST-II. At the same time, the prediction and the potential signal regions all appear to be in serious conflict with the exclusion limits from XENON10 and XENON100 and in partial disagreement with some of the other limits.

One of the important proposals in the literature to resolve the light-WIMP inconsistencies among the direct search data is to allow substantial violation of isospin symmetry in the WIMP-nucleon interactions [26]. It turns out that the tension can be partially alleviated if the effective WIMP couplings f_p and f_n to the proton and neutron, respectively, obey the ratio $f_n/f_p \simeq -0.7$ [26].

We now apply this requirement to the THDM+D and the new CDMS II data. Since k_f^H, as in Eq. (8), are free parameters, allowing them to deviate from the choices $k_f^H = 1$ above, which respect isospin, can lead to large isospin violation in the darkon couplings to the proton and neutron. This has been done in Ref. [19], with $f_{p,n}$ being replaced by the effective couplings $g_{ppH,nnH}$ of H to the proton and neutron, respectively. The result is that, although the prediction is too low compared to the DAMA and CoGeNT areas by a factor of a few, part of it escapes the stringent bounds from XENON10 and XENON100 as well as the new limit (blue solid curve) from CDMS II [11]. All this is shown in Fig. 2, where the experimental data have been reproduced with the WIMP-nucleon couplings fulfilling $f_n = -0.7 f_p$. The orange curve is the largest prediction corresponding to $\lambda_H k_u^H = \mathcal{O}(10^3)$, $k_u^H \sim -2k_d^H$, and the other k_f^H being negligible by comparison [19].[1] The lightly shaded (light orange) region below the orange curve corresponds to the prediction with other choices of k_f^H subject to the relic data and $f_n = -0.7 f_p$ requirements.

It is interesting to notice that in Fig. 2 nearly all of the blue (cyan) area representing the 68% CL (90% CL) possible CDMS II signal is allowed by all of the present limits, although it no longer overlaps with the CoGeNT (magenta) patch. Moreover, most of the allowed regions are within the prediction range (light orange region). Thus the THDM+D with a light darkon is well consistent with the WIMP inkling from CDMS II, whether the WIMP-nucleon interaction violates isospin or not. Data from future direct detection experiments can be expected to provide extra tests on the light-WIMP hypothesis and therefore also probe the darkon model further.

[1] The enhanced size of $k_{u,d}^H$ confirms the finding of Ref. [27].

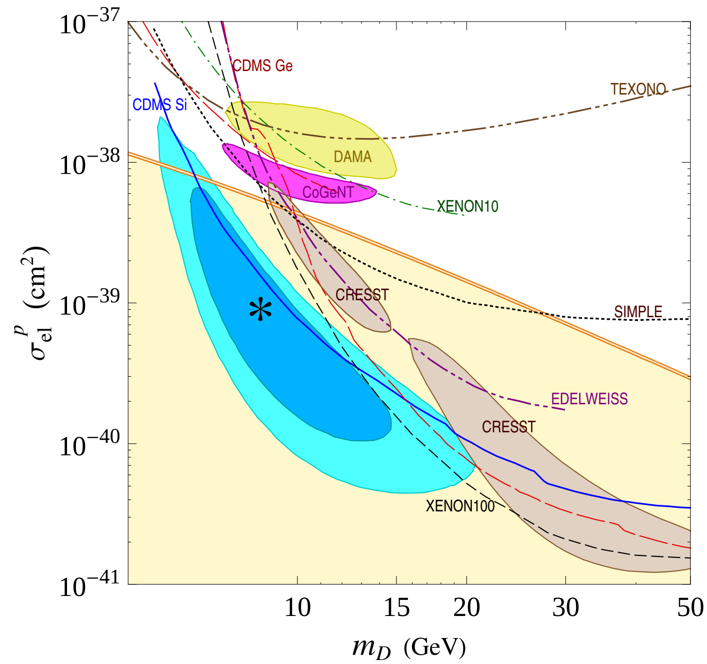

FIG. 2: Darkon-proton cross-section $\sigma_{\rm el}^{p}$ in THDM+D with isospin-violating darkon-nucleon couplings [orange curve and (lightly shaded) light-orange region below it] compared with the direct search results from Fig. 1(b) reproduced using WIMP-nucleon couplings satisfying $f_n = -0.7 f_p$.

III. CONCLUSIONS

The three excess events detected by CDMS II may have been the first evidence of WIMP collisions with ordinary matter. Most of the WIMP parameter space implied by the data can evade all the bounds from other direct detection experiments if the WIMP interactions violate isospin significantly. We have explored this new development in the two-Higgs-doublet model slightly expanded with the addition of a real gauge-singlet scalar particle, the darkon, acting as the WIMP, taking into account the Higgs data from the LHC and Planck determination of the relic density. We find that this model can comfortably account for the discovered Higgs boson and the low-mass WIMP that may have been observed by CDMS II.

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[1] R. Agnese *et al.* [CDMS Collaboration], [arXiv:1304.4279 [hep-ex]].

[2] R. Bernabei *et al.* [DAMA and LIBRA Collaborations], Eur. Phys. J. C **67**, 39 (2010) [arXiv:1002.1028

[astro-ph.GA]].
[3] C.E. Aalseth *et al.* [CoGeNT Collaboration], Phys. Rev. Lett. **106**, 131301 (2011) [arXiv:1002.4703 [astro-ph.CO]]; Phys. Rev. Lett. **107**, 141301 (2011) [arXiv:1106.0650 [astro-ph.CO]].
[4] G. Angloher *et al.*, Eur. Phys. J. C **72**, 1971 (2012) [arXiv:1109.0702 [astro-ph.CO]].
[5] J. Angle *et al.* [XENON10 Collaboration], Phys. Rev. Lett. **107**, 051301 (2011) [arXiv:1104.3088 [astro-ph.CO]].
[6] E. Aprile *et al.* [XENON100 Collaboration], Phys. Rev. Lett. **109**, 181301 (2012) [arXiv:1207.5988 [astro-ph.CO]].
[7] Z. Ahmed *et al.* [CDMS-II Collaboration], Science **327**, 1619 (2010) [arXiv:0912.3592 [astro-ph.CO]]; D.S. Akerib *et al.* [CDMS Collaboration], Phys. Rev. D **82**, 122004 (2010) [arXiv:1010.4290 [astro-ph.CO]]; Z. Ahmed *et al.* [CDMS-II Collaboration], Phys. Rev. Lett. **106**, 131302 (2011) [arXiv:1011.2482 [astro-ph.CO]].
[8] M. Felizardo *et al.* [SIMPLE Collaboration], Phys. Rev. Lett. **108**, 201302 (2012) [arXiv:1106.3014 [astro-ph.CO]].
[9] E. Armengaud *et al.* [EDELWEISS Collaboration], Phys. Rev. D **86**, 051701 (2012) [arXiv:1207.1815 [astro-ph.CO]].
[10] H.B. Li *et al.* [TEXONO Collaboration], arXiv:1303.0925 [hep-ex].
[11] R. Agnese *et al.* [CDMS Collaboration], [arXiv:1304.3706 [astro-ph.CO]].
[12] D. Hooper, J.I. Collar, J. Hall, D. McKinsey, and C. Kelso, Phys. Rev. D **82**, 123509 (2010) [arXiv:1007.1005 [hep-ph]]; J.I. Collar, arXiv:1103.3481 [astro-ph.CO]; arXiv:1106.0653 [astro-ph.CO]; arXiv:1106.3559 [astro-ph.CO]; C.E. Dahl, J. Hall, and W.H. Lippincott, Phys. Rev. Lett. **108**, 259001 (2012) [arXiv:1111.6192 [astro-ph.CO]]; D. Hooper, Phys. Dark Univ. **1**, 1 (2012) [arXiv:1201.1303 [astro-ph.CO]].
[13] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716**, 1 (2012) [arXiv:1207.7214 [hep-ex]]; S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716**, 30 (2012) [arXiv:1207.7235 [hep-ex]]; http://press.web.cern.ch/press-releases/2013/03/new-results-indicate-particle-discovered-cern-higgs-boson.
[14] P.A.R. Ade *et al.* [Planck Collaboration], arXiv:1303.5062 [astro-ph.CO].
[15] V. Silveira and A. Zee, Phys. Lett. B **161**, 136 (1985); C.P. Burgess, M. Pospelov, and T. ter Veldhuis, Nucl. Phys. B **619**, 709 (2001) [arXiv:hep-ph/0011335].
[16] X.G. He, S.Y. Ho, J. Tandean, and H.C. Tsai, Phys. Rev. D **82**, 035016 (2010) [arXiv:1004.3464 [hep-ph]]; X.G. He and J. Tandean, Phys. Rev. D **84**, 075018 (2011) [arXiv:1109.1277 [hep-ph]].
[17] C. Bird, R. Kowalewski, and M. Pospelov, Mod. Phys. Lett. A **21**, 457 (2006) [arXiv:hep-ph/0601090]; X.G. He, T. Li, X.Q. Li, and H.C. Tsai, Mod. Phys. Lett. A **22**, 2121 (2007) [arXiv:hep-ph/0701156].
[18] Y. Cai, X.G. He, and B. Ren, Phys. Rev. D **83**, 083524 (2011) [arXiv:1102.1522 [hep-ph]].
[19] X.G. He, B. Ren, and J. Tandean, Phys. Rev. D **85**, 093019 (2012) [arXiv:1112.6364 [hep-ph]].
[20] G.C. Branco, P.M. Ferreira, L. Lavoura, M.N. Rebelo, M. Sher, and J.P. Silva, Phys. Rept. **516**, 1 (2012) [arXiv:1106.0034 [hep-ph]].
[21] T.P. Cheng and M. Sher, Phys. Rev. D **35**, 3484 (1987).
[22] K. Cheung, J.S. Lee, and P.Y. Tseng, arXiv:1302.3794 [hep-ph]; A. Falkowski, F. Riva, and A. Urbano, arXiv:1303.1812 [hep-ph]; P.P. Giardino, K. Kannike, I. Masina, M. Raidal, and A. Strumia, arXiv:1303.3570 [hep-ph]; J. Ellis and T. You, arXiv:1303.3879 [hep-ph].
[23] C. Savage, G. Gelmini, P. Gondolo, and K. Freese, JCAP **0904**, 010 (2009) [arXiv:0808.3607 [astro-ph]].
[24] C. Kelso, D. Hooper, and M.R. Buckley, Phys. Rev. D **85**, 043515 (2012) [arXiv:1110.5338 [astro-ph.CO]].

[25] J.R. Ellis, K.A. Olive, and C. Savage, Phys. Rev. D **77**, 065026 (2008) [arXiv:0801.3656 [hep-ph]]; R.D. Young and A.W. Thomas, Nucl. Phys. A **844**, 266C (2010) [arXiv:0911.1757 [hep-lat]].

[26] A. Kurylov and M. Kamionkowski, Phys. Rev. D **69**, 063503 (2004) [arXiv:hep-ph/0307185]; F. Giuliani, Phys. Rev. Lett. **95**, 101301 (2005) [arXiv:hep-ph/0504157]; J.L. Feng, J. Kumar, D. Marfatia, and D. Sanford, Phys. Lett. B **703**, 124 (2011) [arXiv:1102.4331 [hep-ph]].

[27] X. Gao, Z. Kang, and T. Li, JCAP **1301**, 021 (2013) [arXiv:1107.3529 [hep-ph]].